University of Southern California

LANGLEY GRANT
IN-18-CR

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Final Technical Report

NASA Research Grant
USC Account No. 53-4507-0031

Evaluation of on–Line Pulse Control for Vibration Suppression in Flexible Spacecraft

Building on the results of a feasibility study conducted under NASA Research Grant No. -1-471, an evaluation was performed on a vibration suppression technique developed by the Principal Investigators. Specifically, the following analytical and experimental studies were conducted:

Simulation Studies

A numerical simulation study was performed, by means of a large-scale finite element code capable of handling large deformations and/or nonlinear behavior, to investigate the suitability of the nonlinear pulse-control algorithm to suppress the vibrations induced in the SCOLE components under realistic maneuvers. Among the topics investigated were the effects of various control parameters on the efficiency and robustness of the vibration control algorithm.

Sample results are shown in the Appendix.

Analytical Studies

As part of the Ph. D. research of a student in electrical engineering, advanced nonlinear control techniques were applied to an idealized model of some of the SCOLE components to develop an efficient algorithm to determine the optimal locations of point actuators, considering the hardware on the SCOLE project as distributed in nature. A Bernoulli-Euler beam was used to represent the structure attaching the antenna to the orbiter. The control was obtained from a quadratic optimization criterion, given in terms of the state variables of the distributed system.

The main ideas behind this approach are summarized in a paper by Chassiakos and Bekey (1986) titled "On the Modelling and Control of a Flexible Manipulator Arm by Point Actuators," a copy of which is attached.

Experimental Studies

An experimental investigation was performed on a model flexible structure resembling the essential features of the SCOLE components, and electrodynamic and electrohydraulic actuators were used to investigate the applicability of the control algorithm with such devices in addition to mass-ejection pulse generators using compressed air.

Sample results from this study are included in the Appendix.

Meetings

During the period 17-18 November 1986, one of the PI's (R.K. Miller) participated in the Third SCOLE Workshop Concerning the NASA/IEEE Design Challenge and he presented a detailed

report covering the analytical and experimental studies discussed above.

For convenience, the Appendix contains a copy of the transparencies that summarize our accomplishments during the last year of our NASA contract.

Evaluation of On-Line Pulse Control for Vibration Suppression in Flexible Spacecraft

by

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EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT

G.A. Bekey, S.F. Masri, R.K. Miller

University of Southern California
Los Angeles, CA

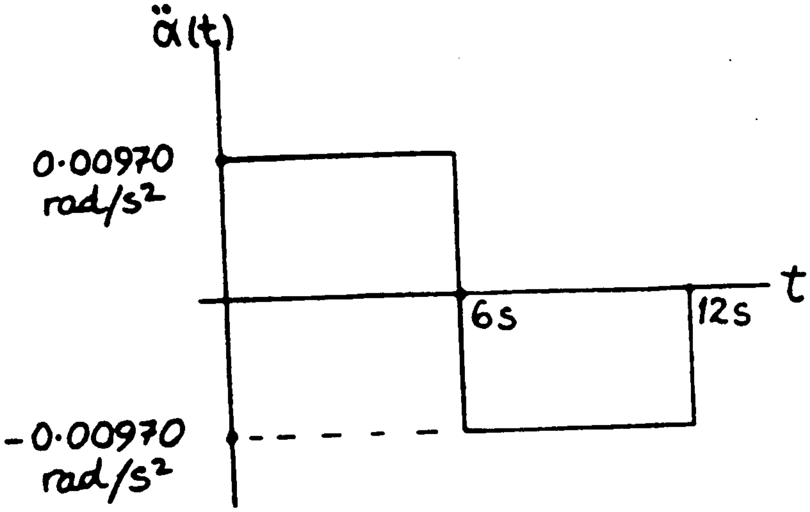
OUTLINE

I. Objective

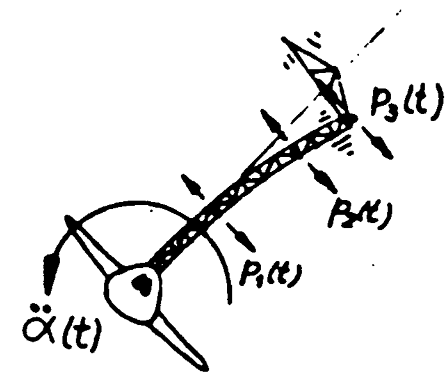
II. Modeling Issues
- Beam vs. Truss
- NL-FEM, numerical problems

III. Control Issues
- ED Pulse Actuator Development
- Pseudo Pulse Algorithm Dev.
- Large NL simulation Problems

OVERALL OBJECTIVE



(Gene Lin, 1984 SCOLE Mtg.)

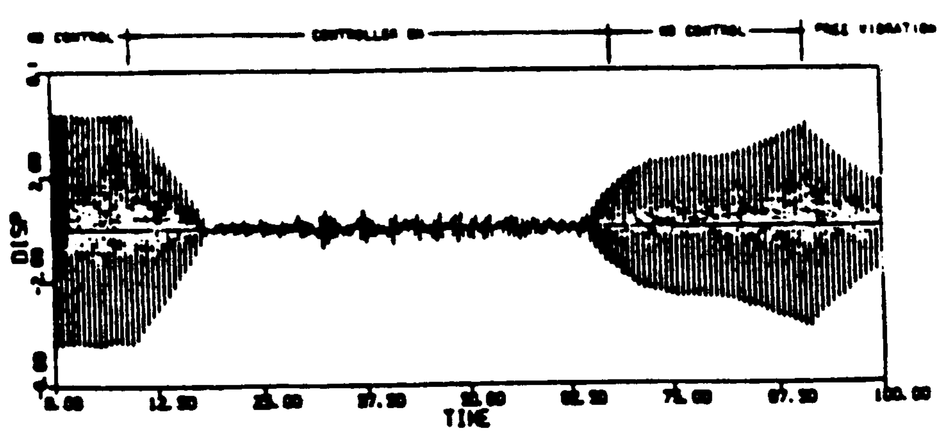


Minimum Time 20° Slew Maneuver

Mass-Ejection Pulse Control Strategy:

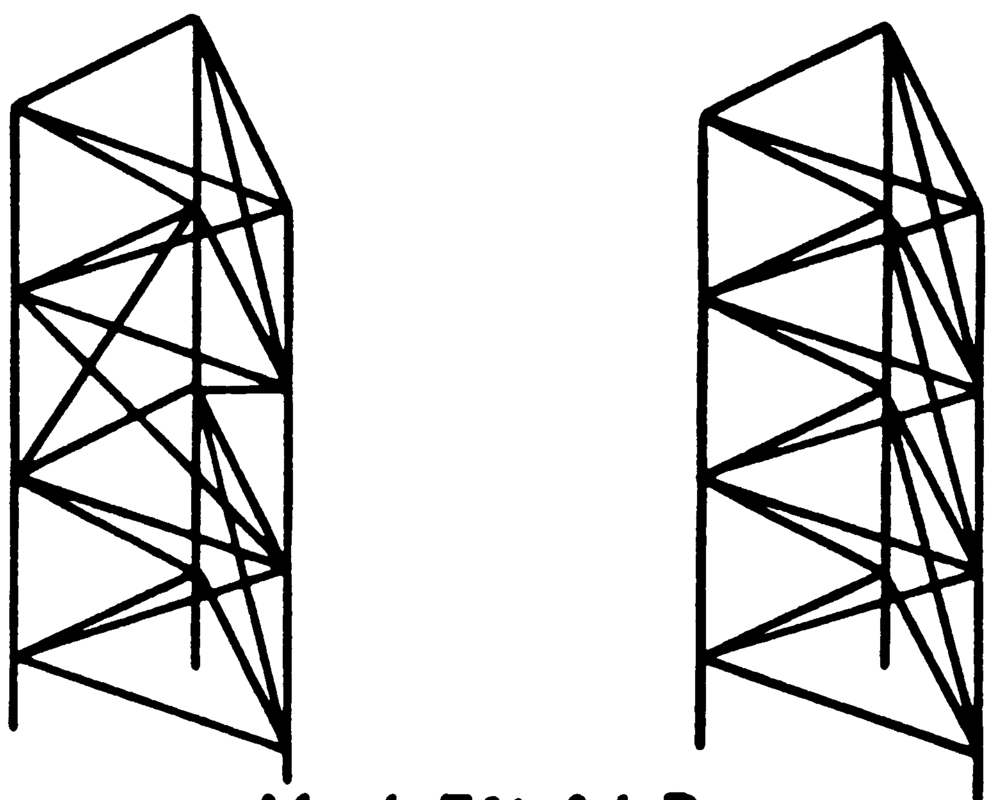
$$p_i(t) = \begin{cases} -c_i \, \mathrm{sgn}(v_i)|v_i|^{n_i}; & t_{o_i} < t < (t_{o_i} + T_{d_i}) \\ 0; & (t_{o_i} + T_{d_i}) < t < t_{o_{i+1}} \end{cases}$$

Typical Experimental Results:



MODELLING ISSUES

1. Continuous Beam vs. Truss
   - Axial / Torsional Coupling
   - Local Member Participation in Modes
   - Parametric Resonance Problems



Mast Flight Beam

Alternating Bay Diagonals

Identical Bay Diagonals

LINEAR TRUSS RESULTS

2. Linear Finite Element Model Characteristics
   - COFS-I Hardware Configuration
   - 54 Bays, 60m
   - 171 nodes, 486 elements, 522 D. of F.
   - July 1986 data for member characteristics from Astro Aerospace Corp./Harris Corp.
   - Match modal results with Astro/Harris
   - Transient Response Simulations:
     - Rayleigh damping: $\zeta_1 = 1\%$, $\zeta_{12} = 10\%$
     - Sine-sweep, tip excitation
     - Nonstationary Random, tip excitation
     - Harmonic, base excitation

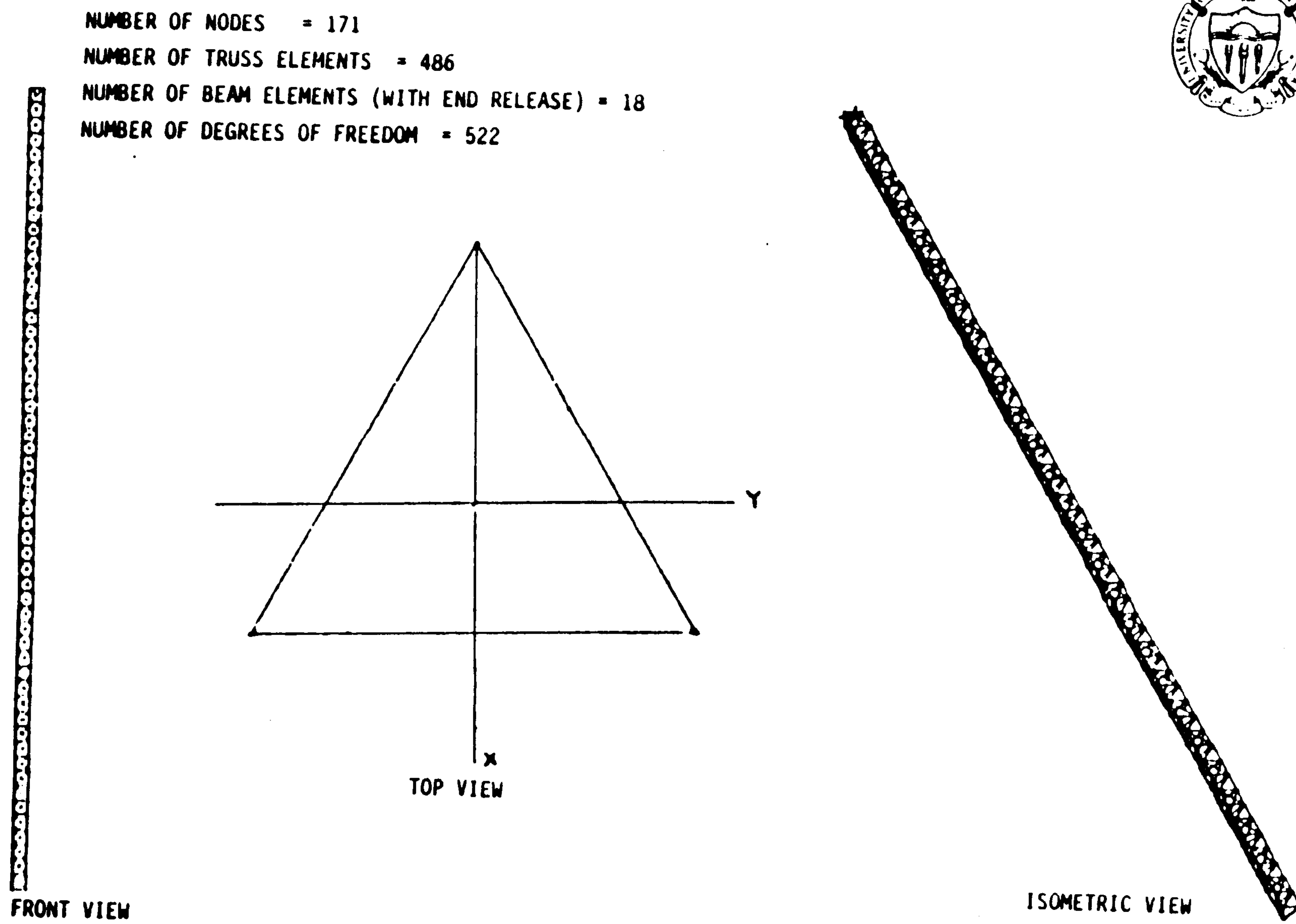
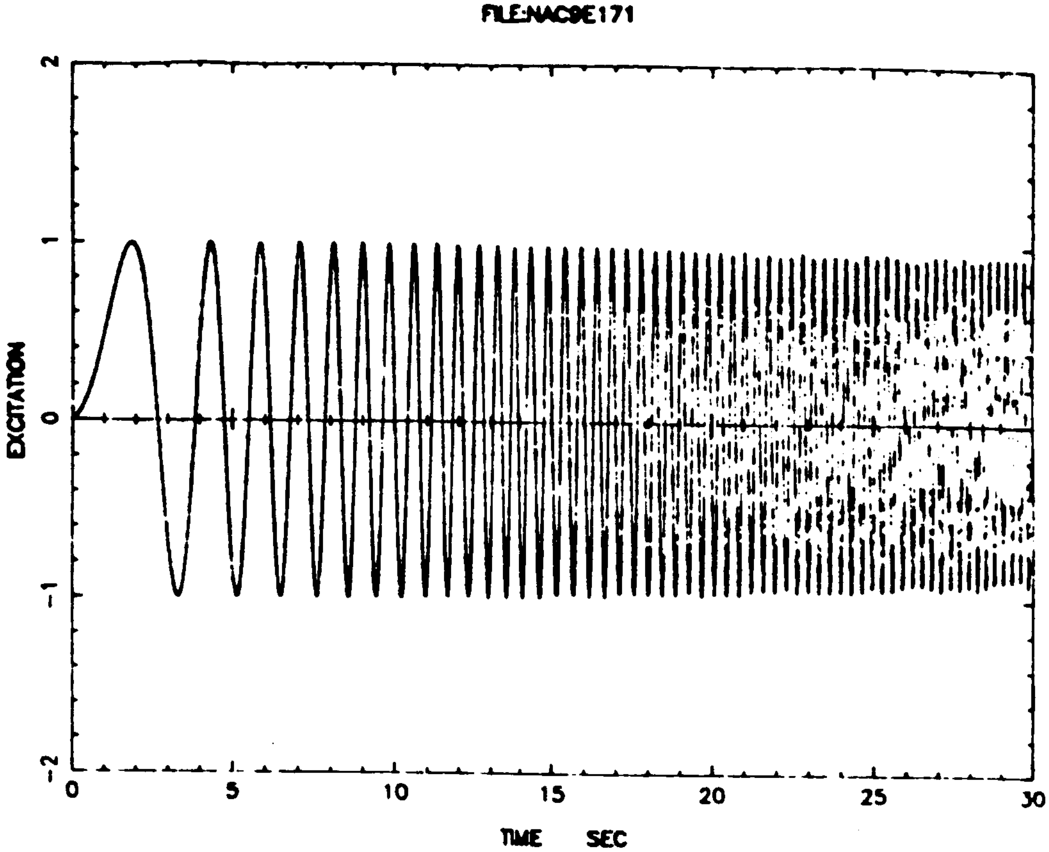


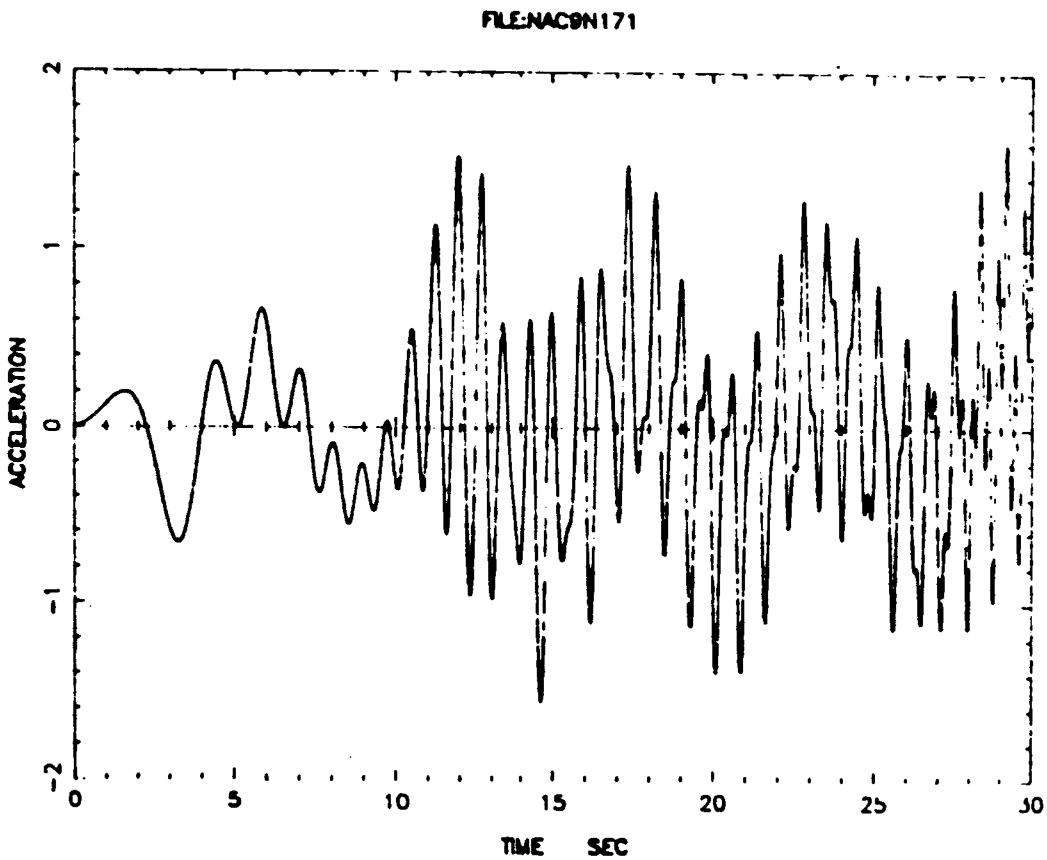
FIG. 1. NONLINEAR THREE-DIMENSIONAL FINITE ELEMENT MODEL OF COFS I MAST

	NASA RESULTS MAST ON RIGID BASE		USC RESULTS MAST ON RIGID BASE	
MODE	FREQUENCY (HZ)	TYPE	FREQUENCY (HZ)	TYPE
1	0.18	1st Bending in Y	0.18	1st Bending in Y
2	0.20	1st Bending in X	0.20	1st Bending in X
3	1.77	2nd Bending in Y	1.60	2nd Bending in Y
4	1.97	2nd Bending in X	1.72	2nd Bending in X
5	2.18	1st Torsion	2.37	1st Torsion
6	5.47	3rd Bending in Y	4.72	3rd Bending in Y
7	6.07	3rd Bending in X	5.07	3rd Bending in X
8	8.12	2nd Torsion	7.70	2nd Torsion
9	11.23	4th Bending in Y	9.29	4th Bending in Y
10	12.44	4th Bending in X	9.93	4th Bending in X
11	12.62	1st Compression	12.49	1st Compression
12	13.51	3rd Torsion	12.82	3rd Torsion

FIG. 3. FIRST 12 NATURAL FREQUENCIES AND MODE SHAPES OBTAINED BY DETERMINING THE EIGEN VALUES AND EIGENVECTORS CORRESPONDING TO THE LINEARIZED VERSION OF THE FINITE ELEMENT MODEL SHOWN IN FIG. 1.



Swept Sine Response - Tip Excit.



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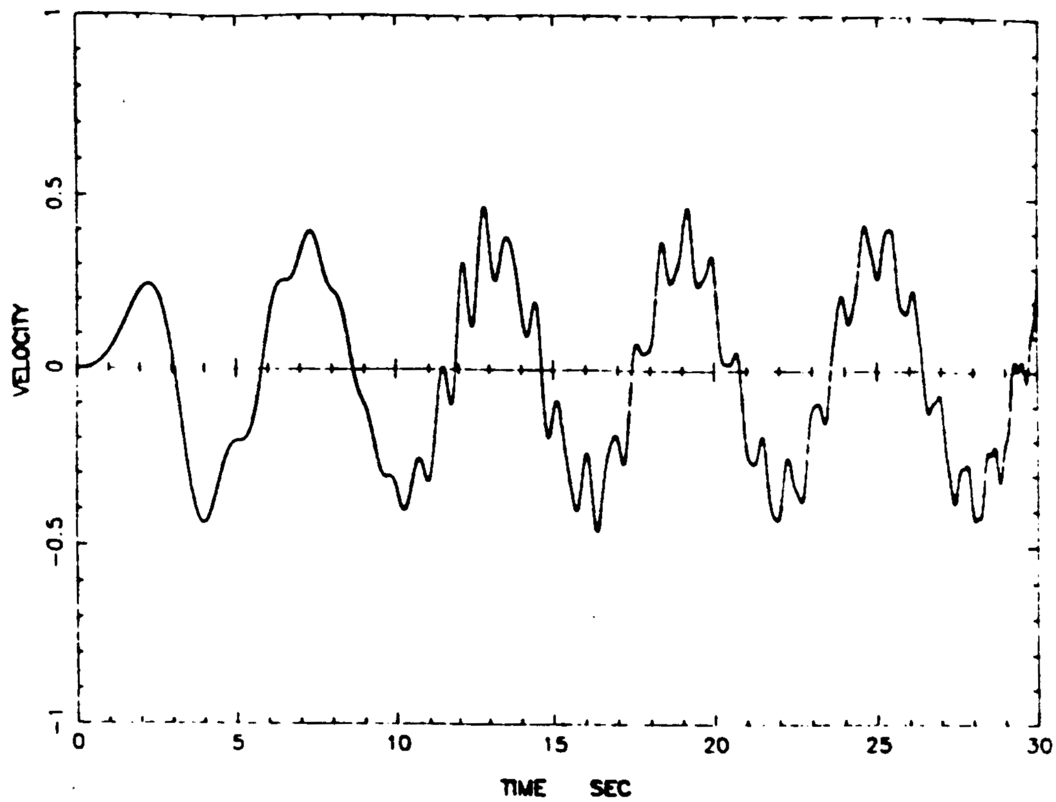
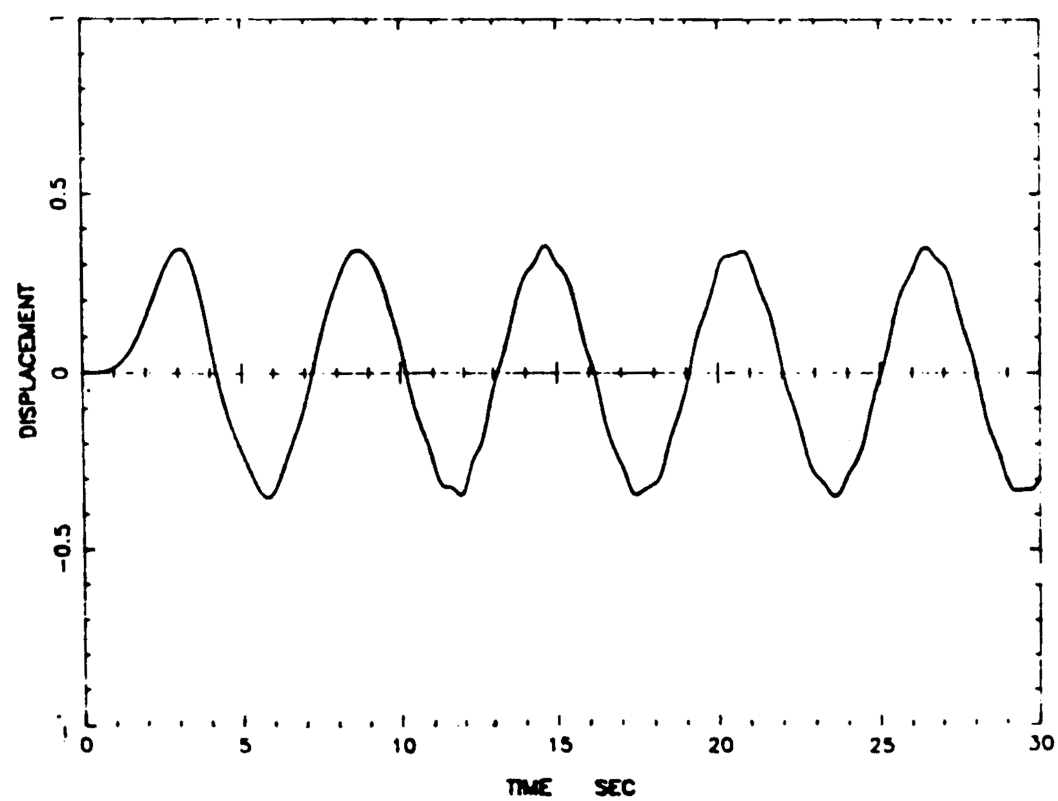
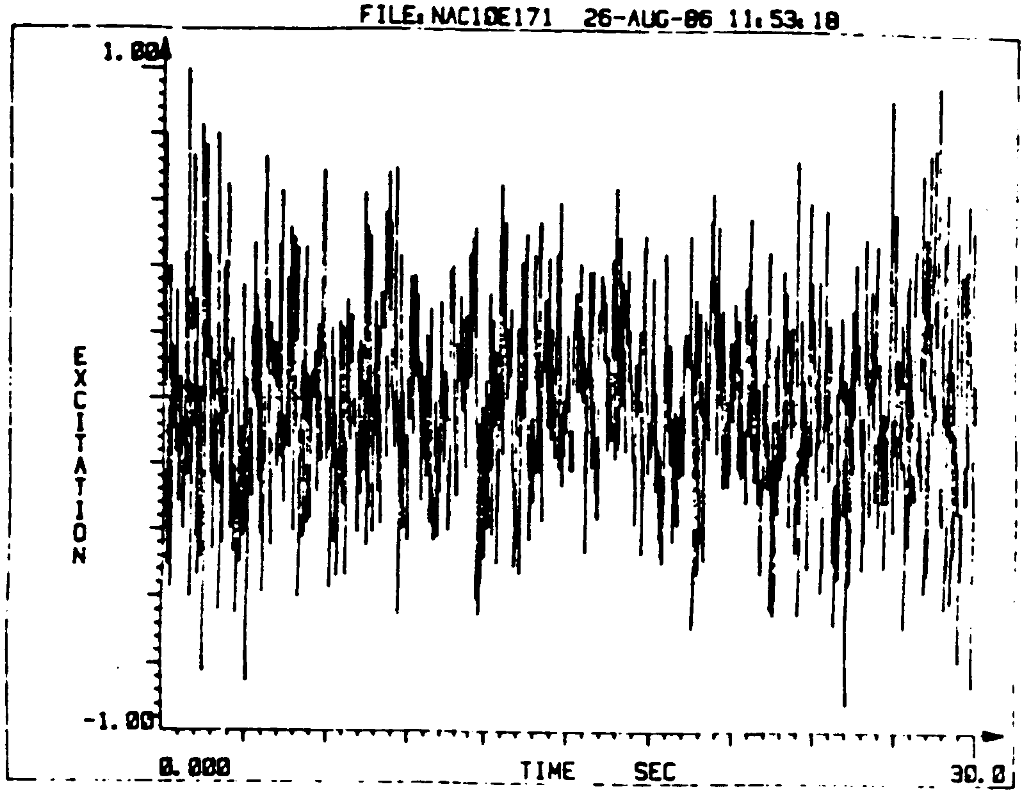


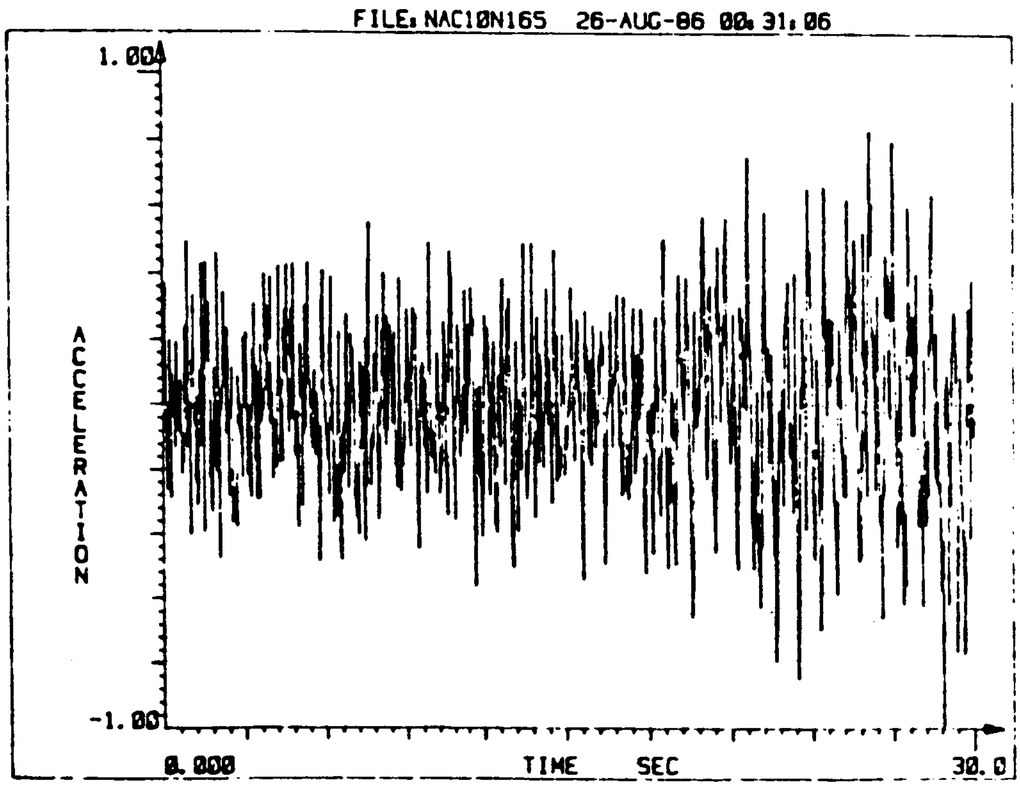
Swept Sine Response - Tip Excit.

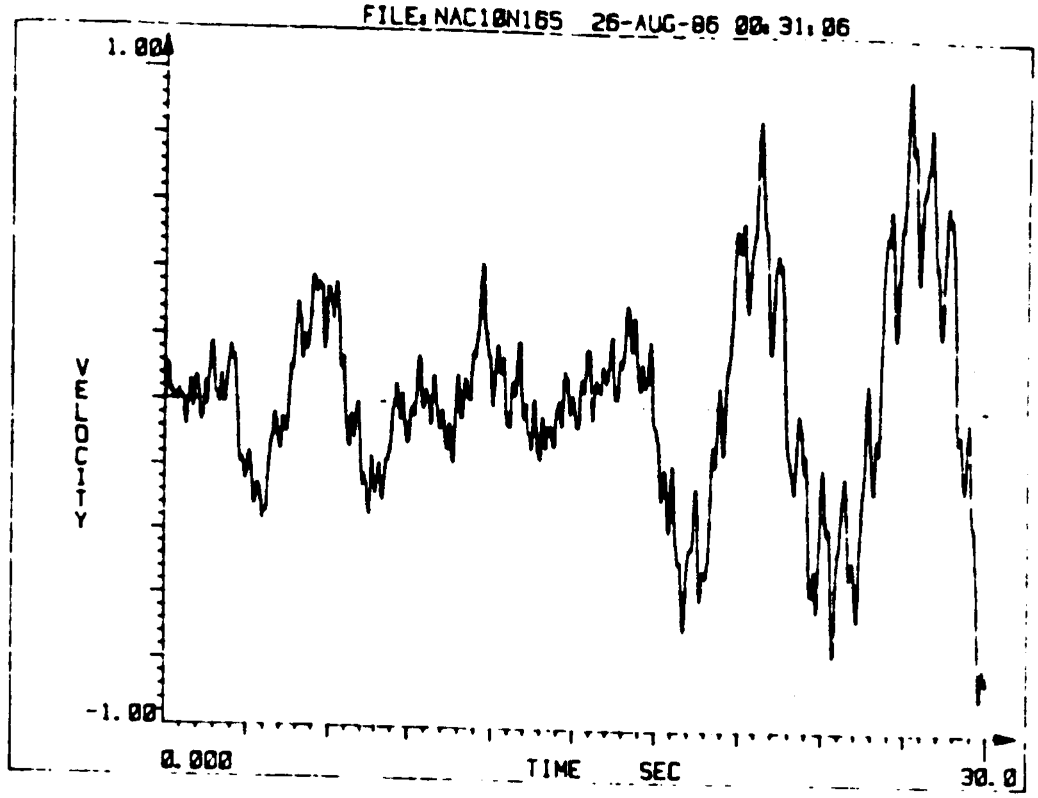
FILE:NAC9N171



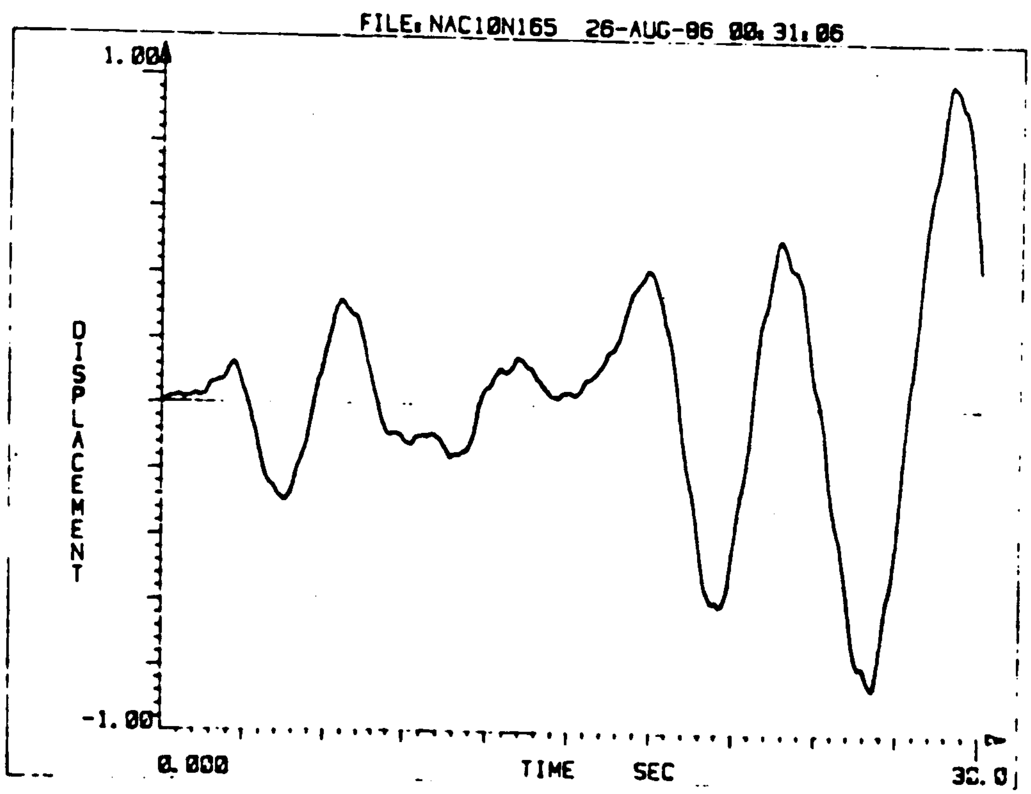


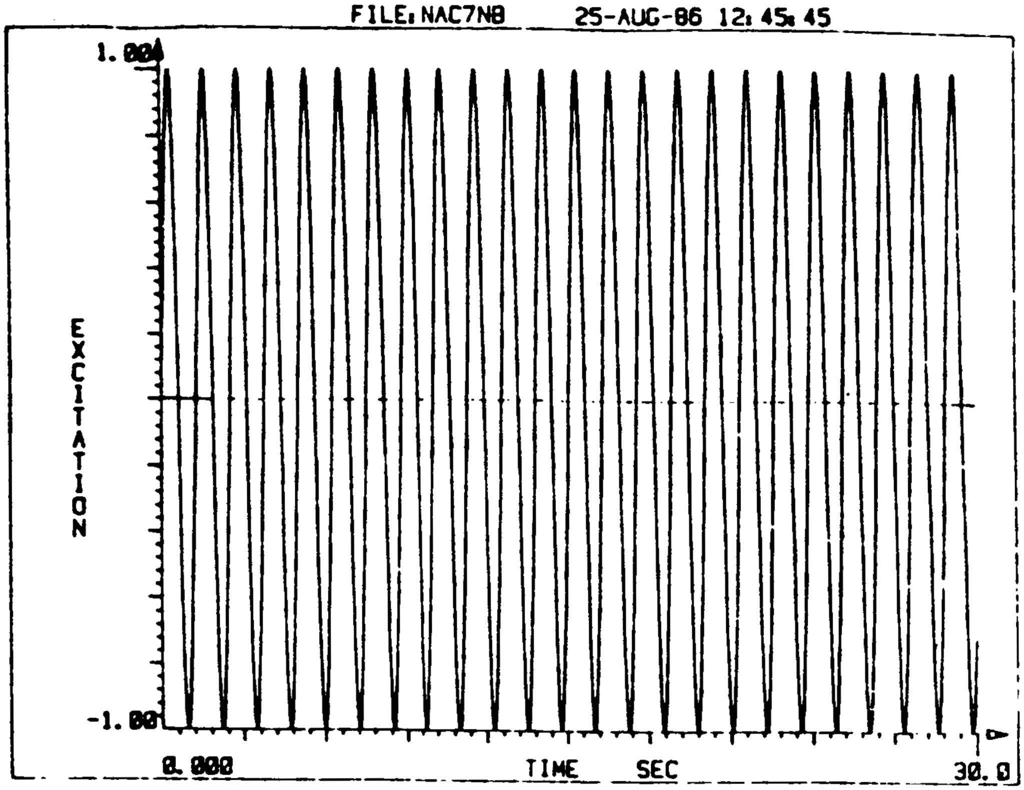
Nonstationary Random Response - Tip Excit



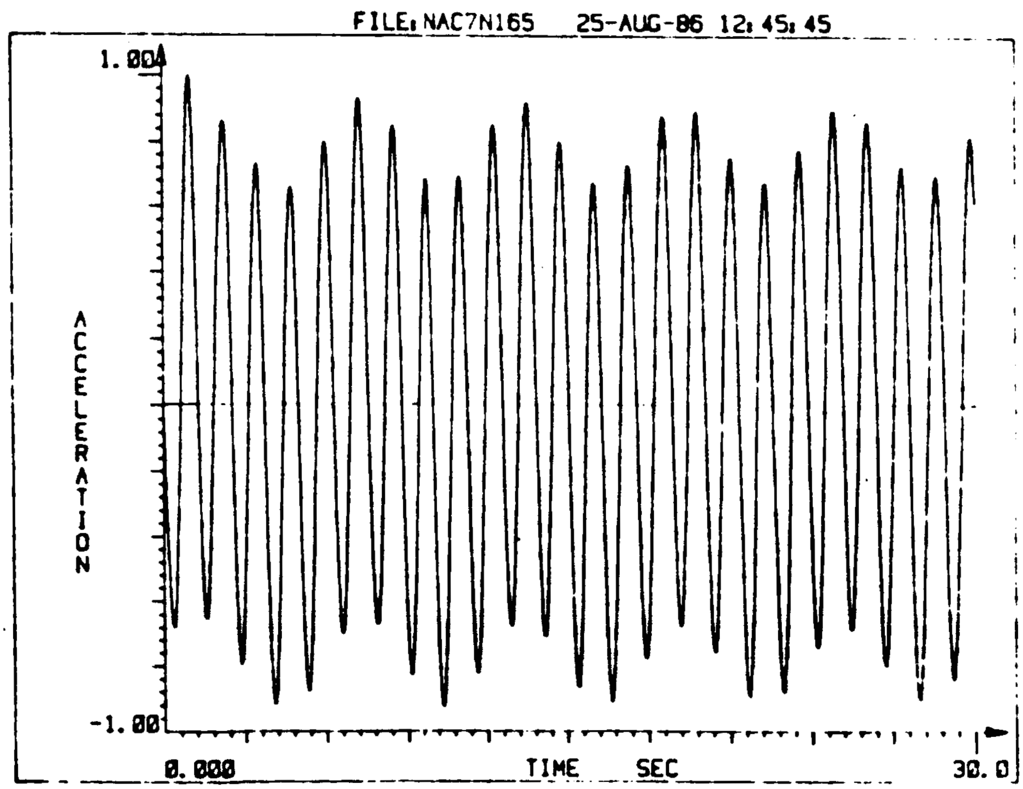


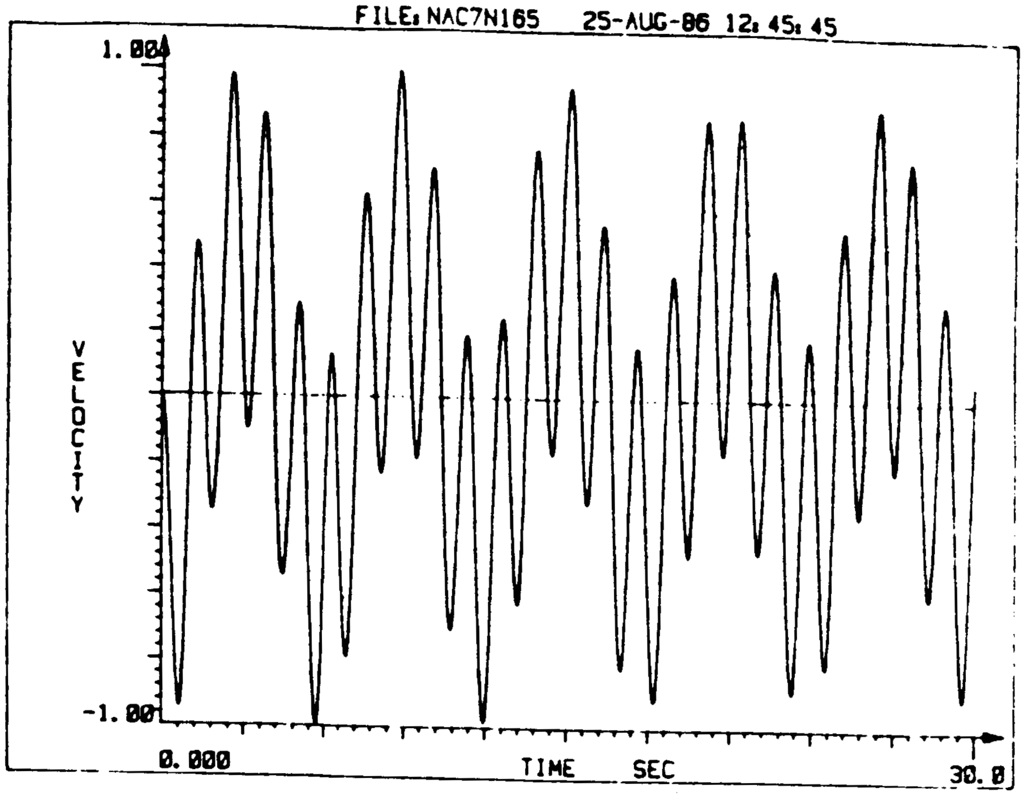
Nonstationary Random Response-Tip Excit



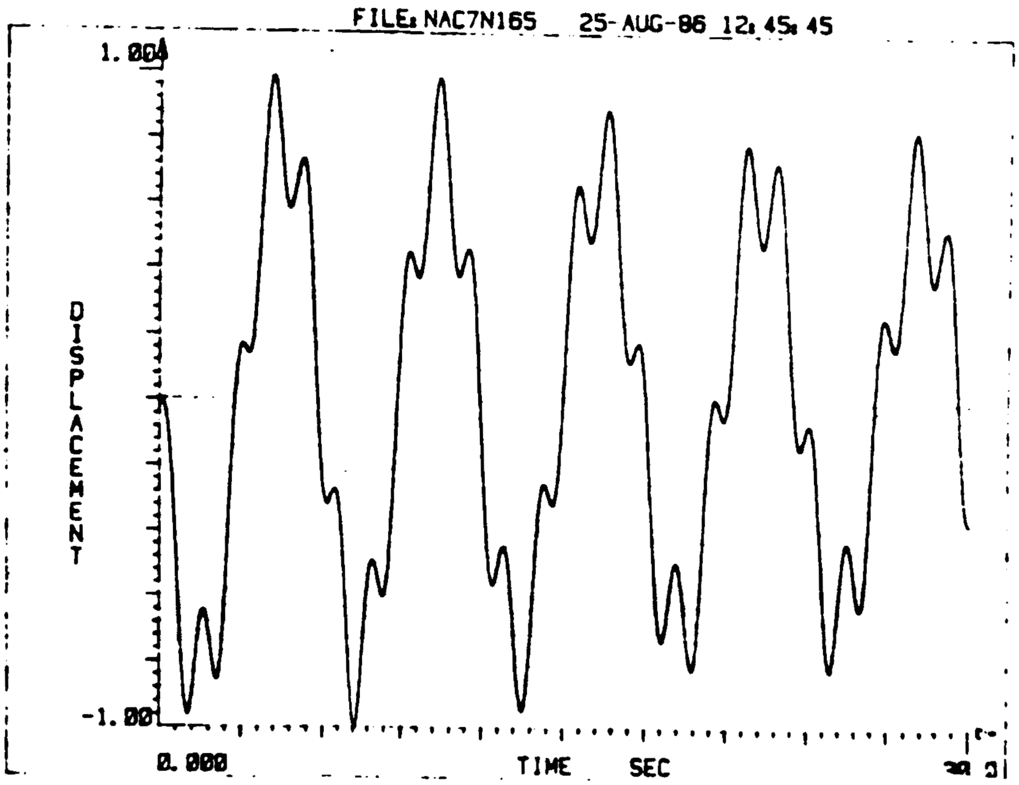


Harmonic Response - Base Excit.





Harmonic Response - Base Excit.

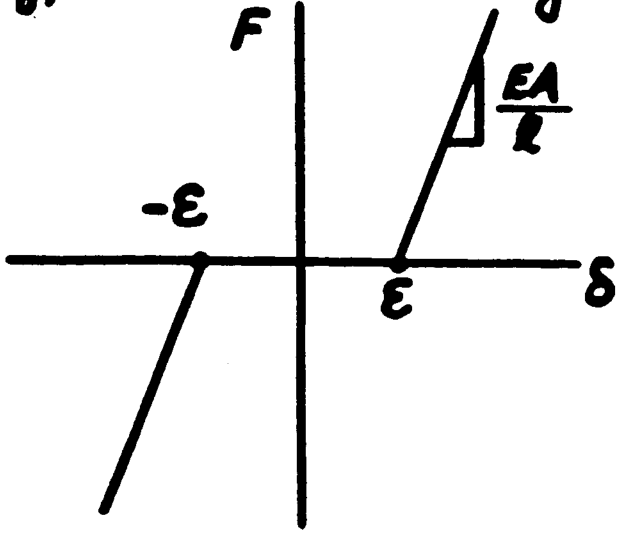


NONLINEAR SIMULATION PROBLEMS

1. Excessive CPU Time
   - 92+ Hours for T=3 Fundamental Period on VAX 11/750
   - Small Δt ($\cong \tau_{12}/1000$) required for numerical stability
2. Model Order Reduction Necessary
   - Nonparametric "RONN" Model - in proces
   - Parametric/Superelement Model-in pro
   - Validity ???

NONLINEAR FINITE ELEMENT MODEL

3. Type of Nonlinearity



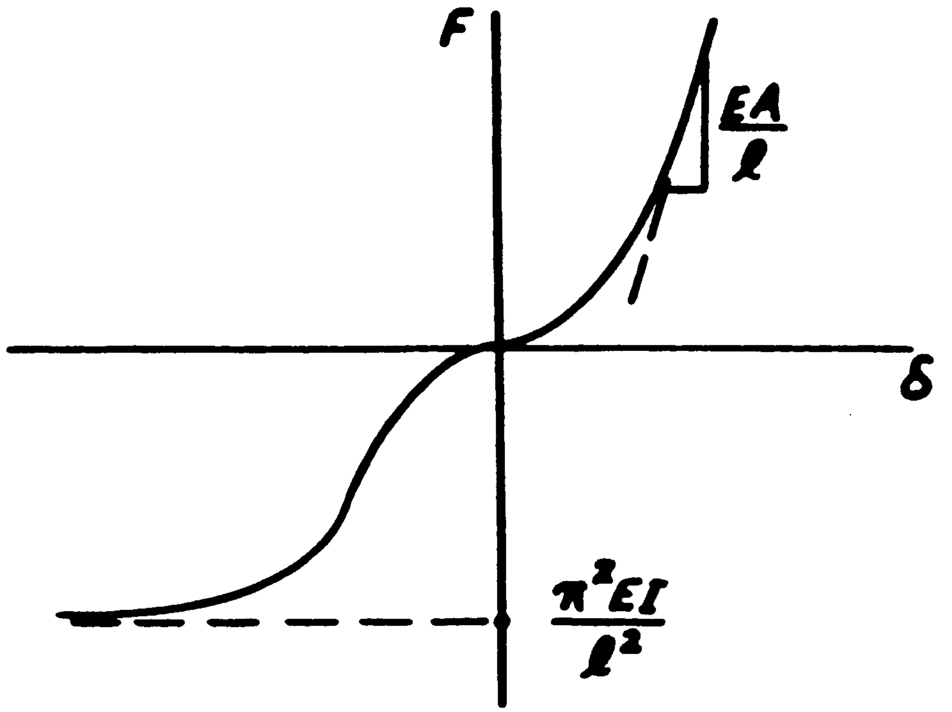
Crude Joint Clearance

$$\left(\frac{\delta}{\varepsilon}\right) = \frac{1}{2} + 0.57|f|\left[\frac{2}{3} - \ln(1.14f)\right]; \quad 0 \le |f| \le 0.63$$

$$= 0.86; \quad |f| > 0.63$$

$$\left(f = \frac{F}{E\ell\varepsilon}\right)$$

Hertzian Joint Contact



Joint Contact + Strut Buckling

NONLINEAR SIMULATION PROBLEMS

1. Excessive CPU Time
   - 92+ Hours for T=3 Fundamental Period on VAX 11/750
   - Small Δt ($\cong \tau_{12}/1000$) required for numerical stability

2. Model Order Reduction Necessary
   - Nonparametric "RONN" Model - in proces
   - Parametric/Superelement Model-in pro
   - Validity ???

CONTROL ISSUES

1. Simulation Progress

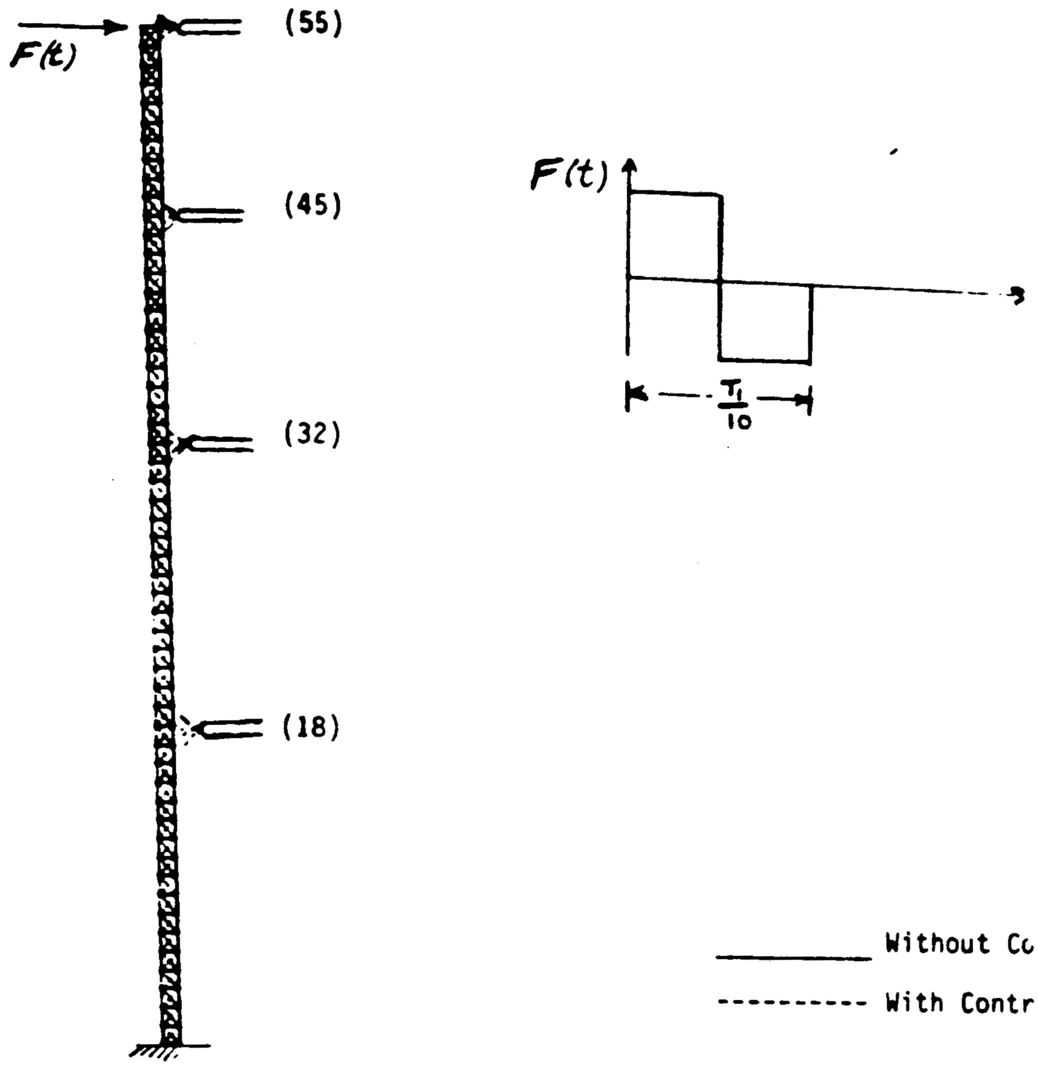
NL-"SAP" FEM

- Lrg. Displ.
- Joint Nonlin.
- R-K, Newmark β, Wilson θ, etc.

PC1-Control Code

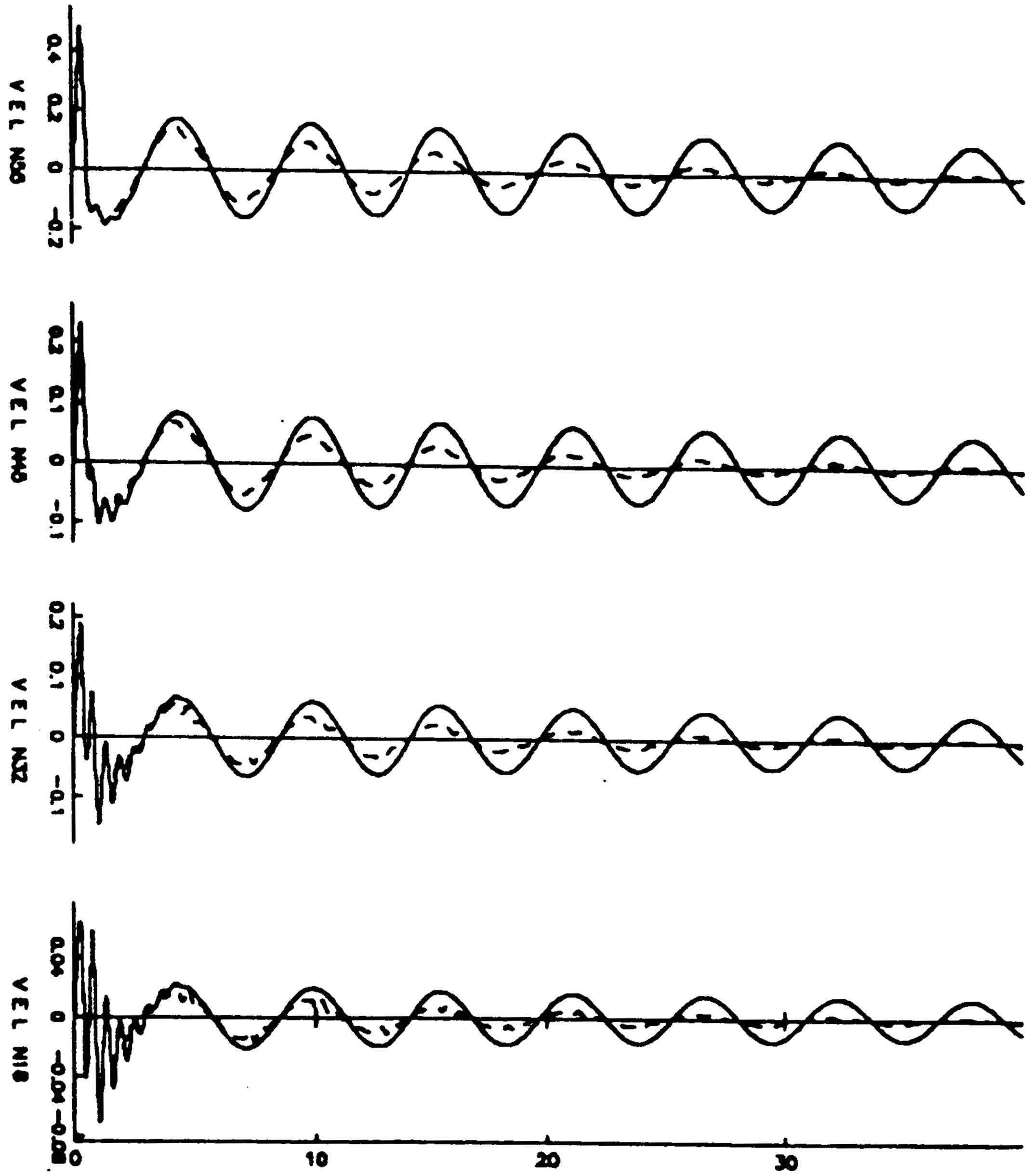
- NL, Adaptive,
- Intermittent
- Special case: $\underset{\sim}{u} = K\underset{\sim}{x}$

1. Time step interupt req'd.
2. Excess storage for state variables
3. Stability and restart capability for time-stepping algorithms



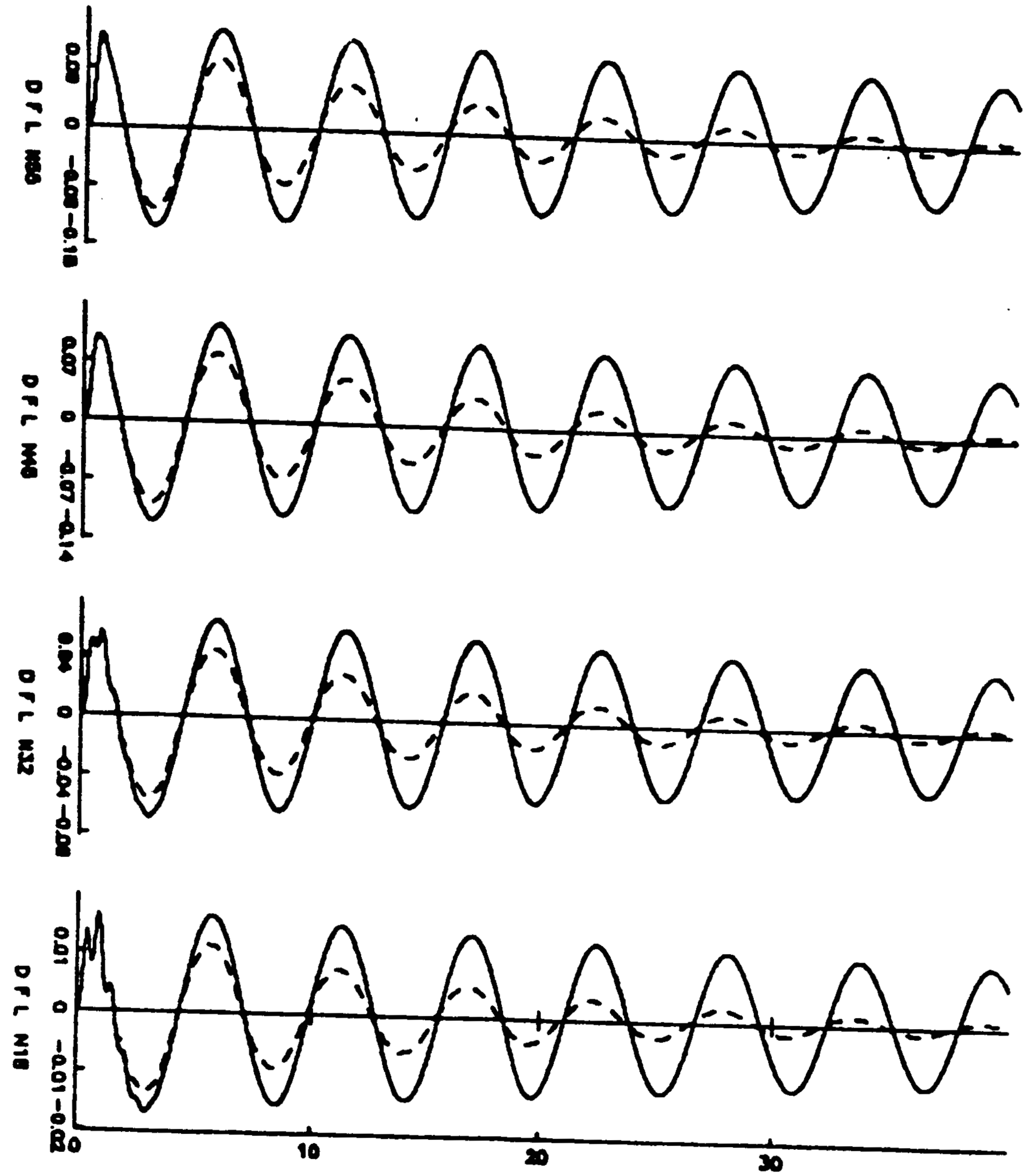
THREE-DIMENSIONAL FINITE ELEMENT MODEL OF COFS I MAST

$C=100 \quad n=1 \quad T_d=0.2$



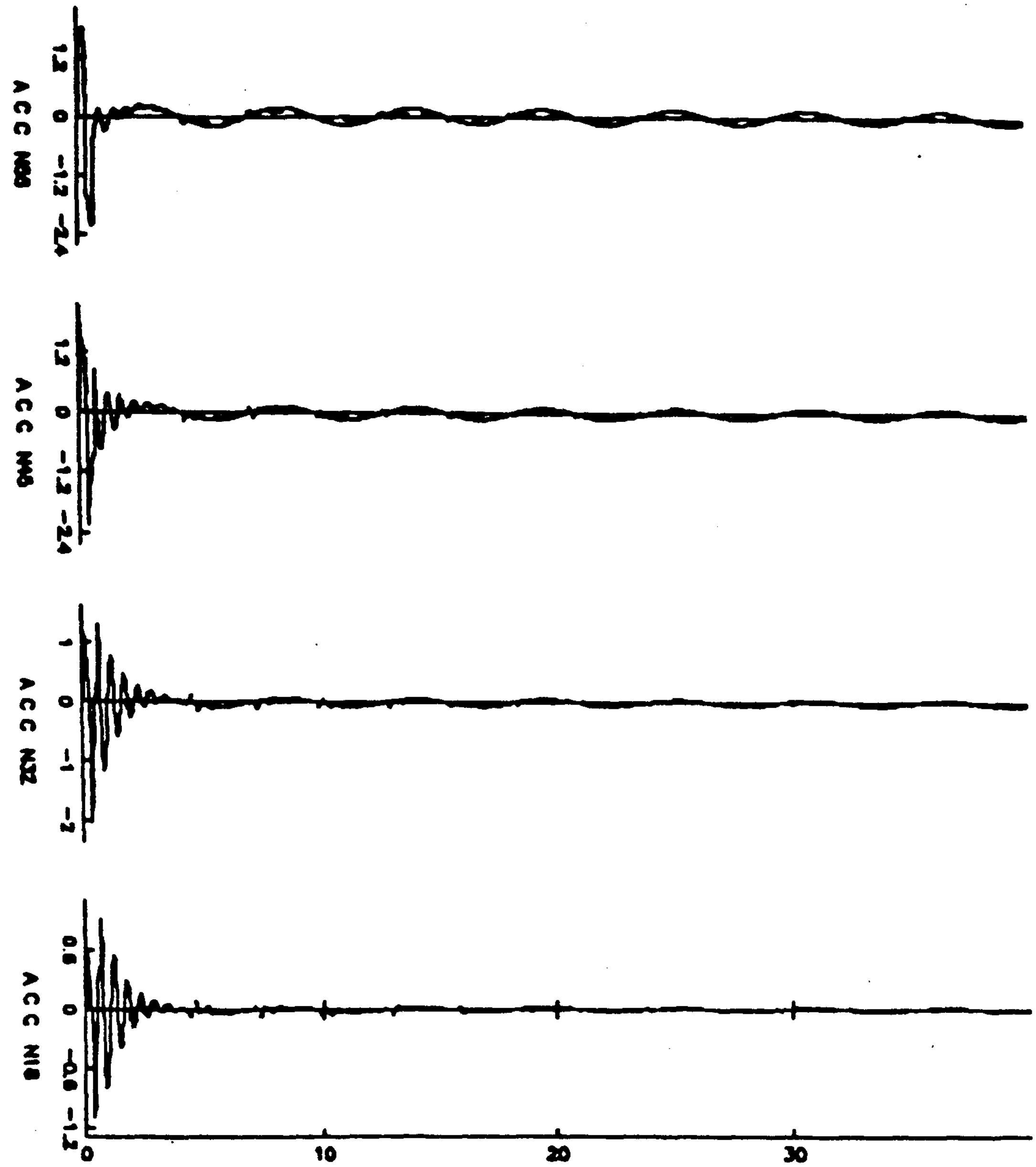
Velocity Response with and without Control

C=100 n=1 T_d=0.2



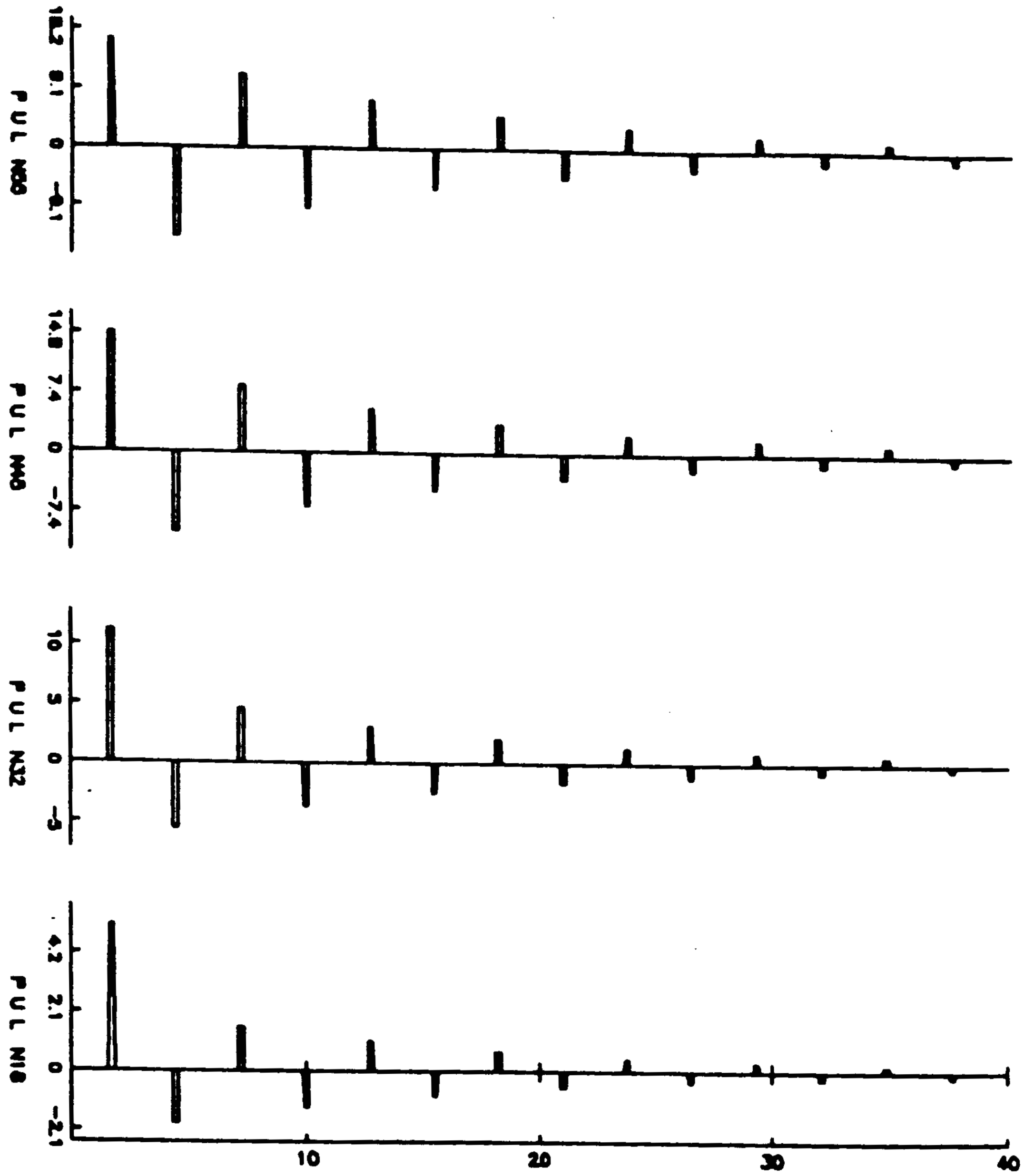
Displacement Response with and without Control

C=100 n=1 T_d=0.2



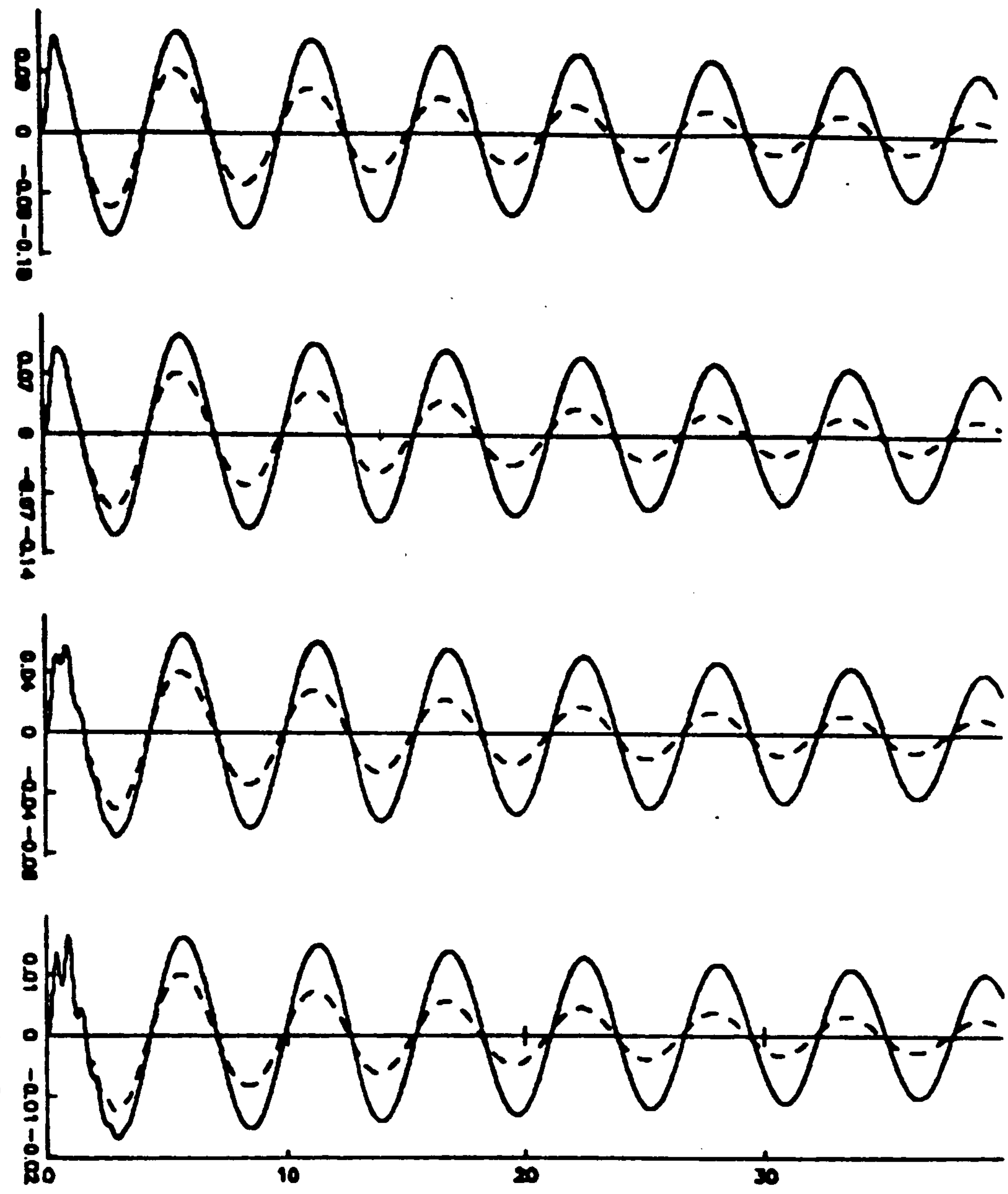
Acceleration Response with and without Control

C=100 n=1 T_d=0.2



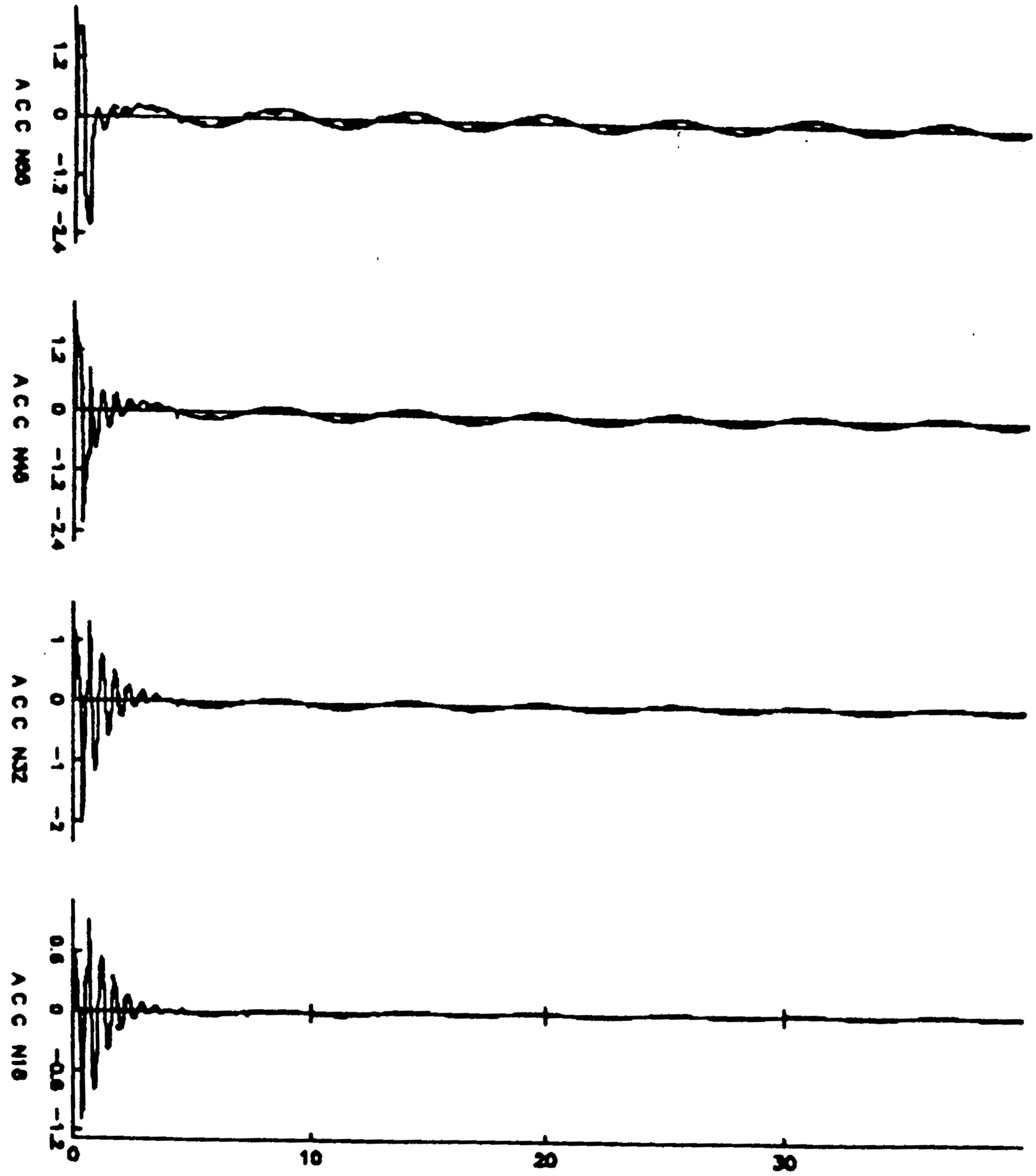
Pulse Control Forces

$C=100 \quad n=2 \quad T_d=0.2$



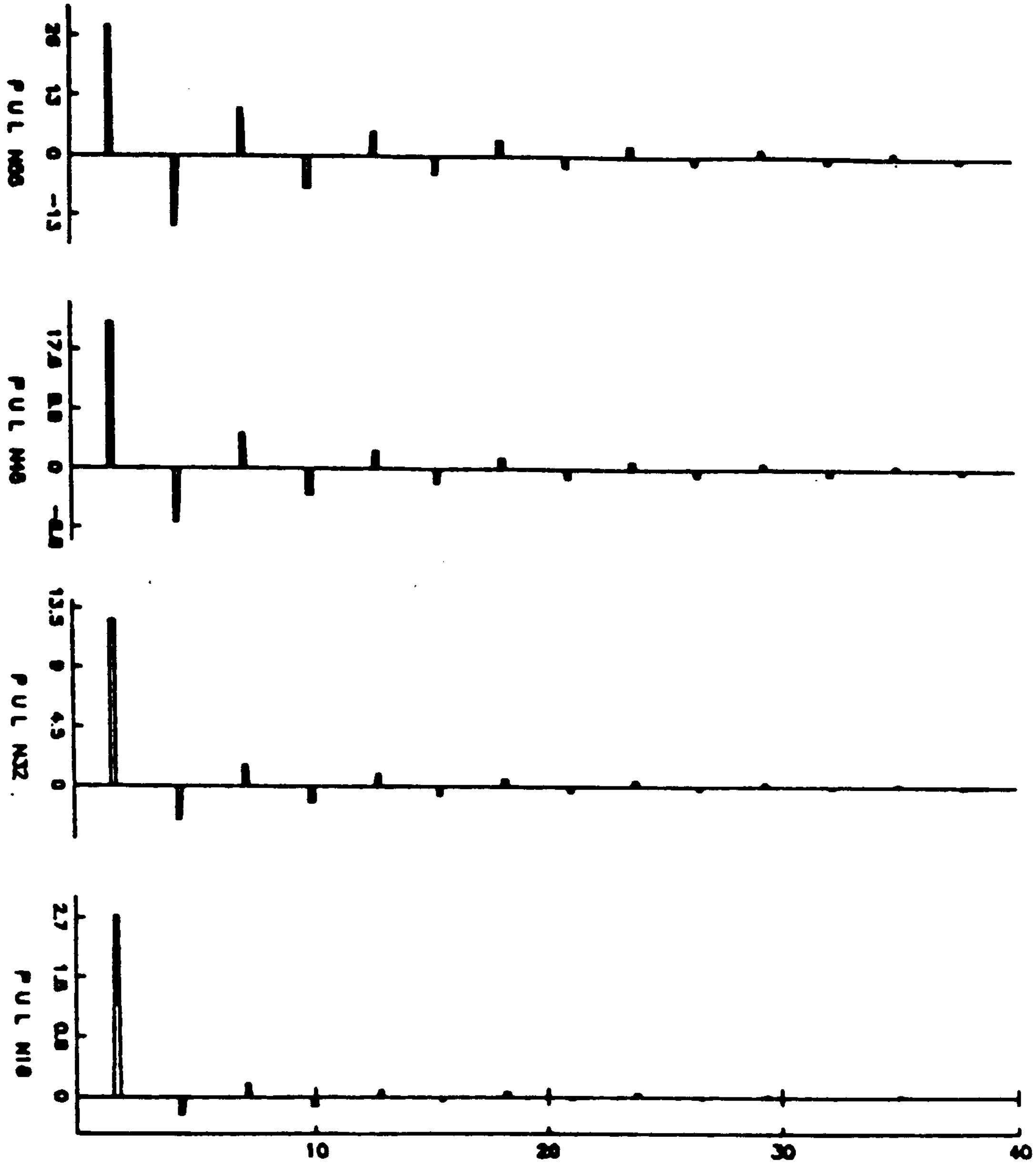
Displacement Response with and without Control

$C=100 \quad n=2 \quad T_d=0.2$

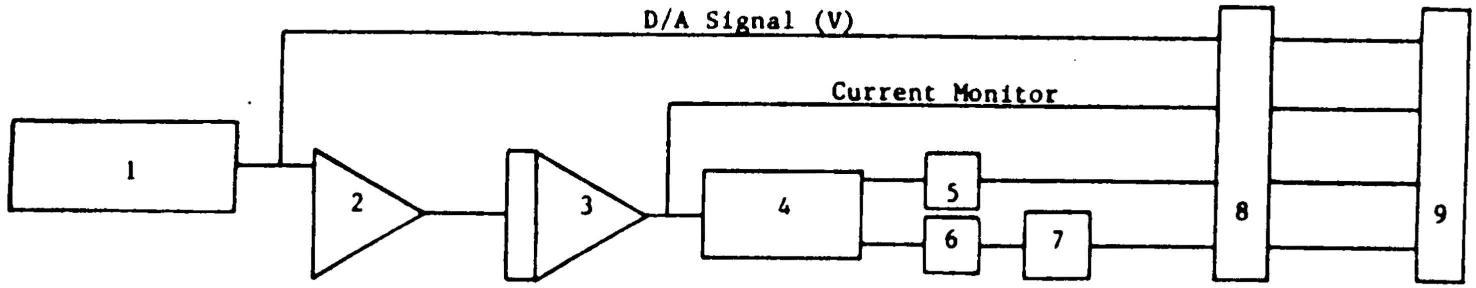


Acceleration Response with and without Control

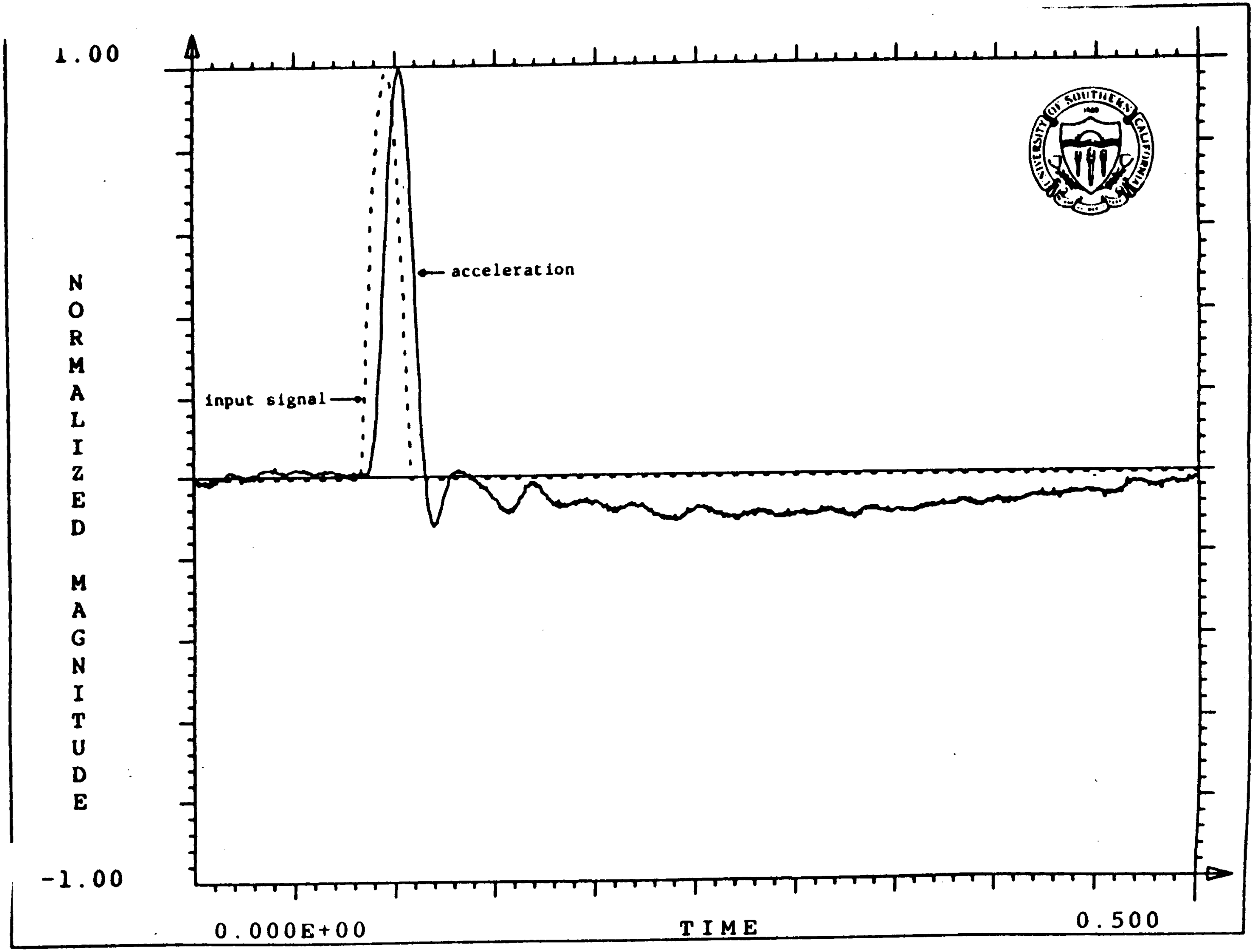
$C=100 \quad n=2 \quad T_d=0.2$



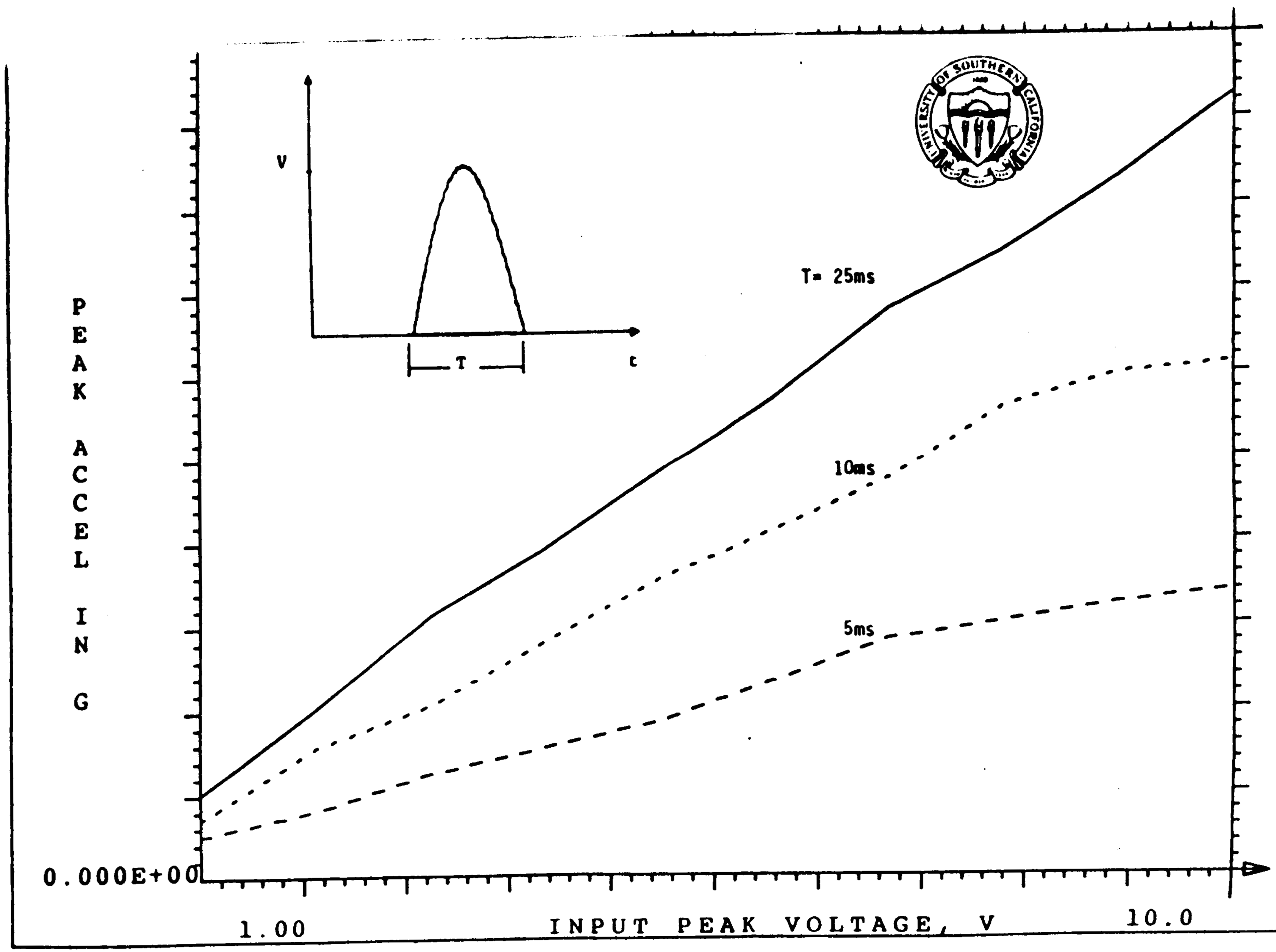
Pulse Control Forces



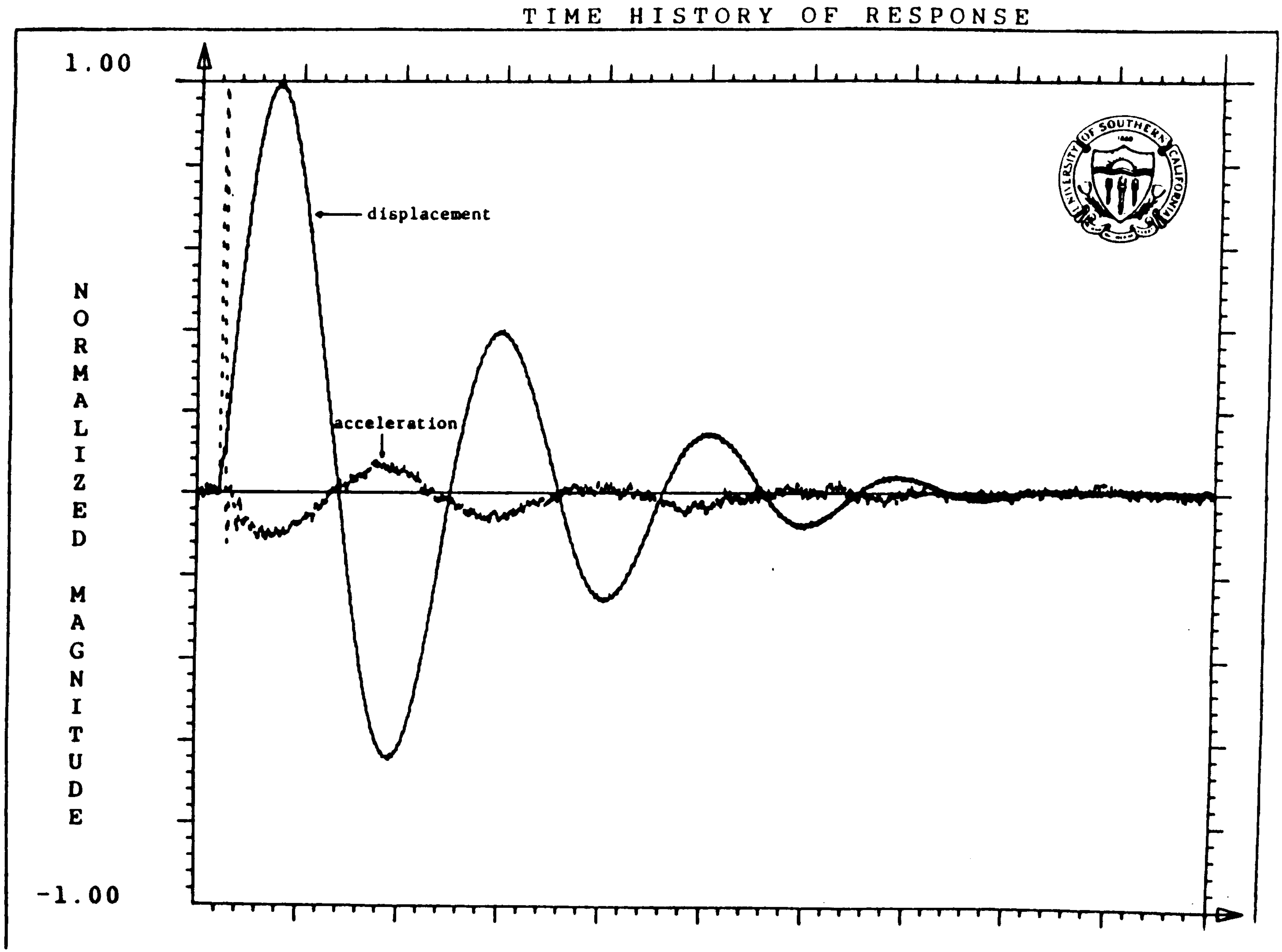
1. PC - XT
2. Operational Amplifier (X2)
3. Power Amplifier
4. Shaker
5. XCDR1 (LVDT)
6. XCDR2 (Piezoresistive accelerometer)
7. Signal Conditioning
8. Digital Filter
9. A/D Converter

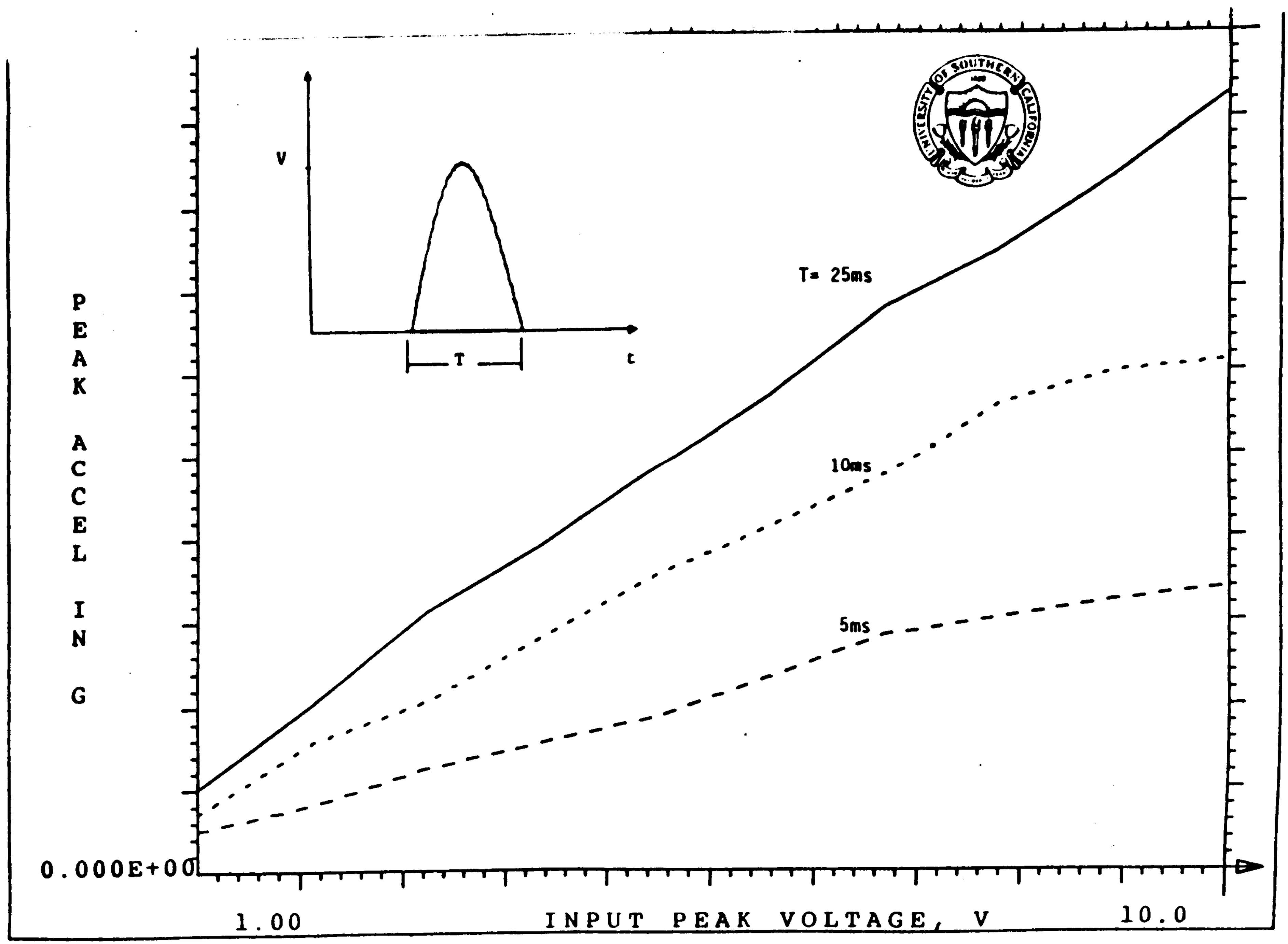


1.00
-1.00
NORMALIZED MAGNITUDE
acceleration
input signal
0.000E+00
TIME
0.500



V
T
t
T= 25ms
10ms
5ms
UNIVERSITY OF SOUTHERN CALIFORNIA
PEAK ACCEL IN G
0.000E+00
1.00
INPUT PEAK VOLTAGE, V
10.0


TIME HISTORY OF RESPONSE
1.00
-1.00
NORMALIZED MAGNITUDE
displacement
acceleration
UNIVERSITY OF SOUTHERN CALIFORNIA


V
T
t
T= 25ms
10ms
5ms
PEAK ACCEL IN G
0.000E+00
1.00
INPUT PEAK VOLTAGE, V
10.0